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THEORY OF PULSE PROPAGATION AND COHERENCE IN FREE ELECTRON LASE--ETC(U)
1982 W B COLSON AFOSR-81-0061
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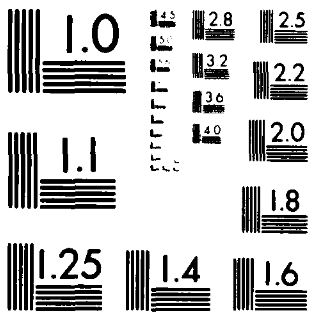

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Pulse propagation in several free electron laser designs is examined along with mode instatilibies, oscillator evolution, spontaneous emission, transverse wavefront propagation, and Coulomb forces. The designs explored include the simple undulator, the tapered undulator, the optical klystron, and the transverse gradient "gain-expansion" magnet.

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Annual Scientific Report (AFOSR-81-0061) - W.B. Colson

Free electron lasers (FELs) amplify the radiation present in a resonant optical cavity with a co-propagating relativistic electron beam traveling along the axis of a long, periodic magnetic field. Specifically proposed has been a study of short pulse propagation and coherence in free electron lasers. In FELs where an electron pulse interacts with an accelerating R.F. field as in a linac, the necessity of small emittance and energy spread often yields short electron pulses, a few millimeters long. Coherence is another important matter. The FEL gain mechanism relies on the long-range order of the optical wave; an electron must experience one coherent optical wavelength for each period of the magnet. Considerations of optical pulse propagation cannot be completely separated from the noise studies. Even in steady-state, parts of the optical pulse are continually evolving from noise and reshaping the pulse structure. Transverse optical effects can also modify pulse propagation and coherence. The combining of pulse propagation with transverse effects, noise, and coherence will give a nearly complete description of free electron laser systems.

Theoretical Progress

Our goal has been to provide a clear, intuitive description of free electron laser phenomena so that we have a foundation for future experiments and FEL designs. Significant progress has been made in the first year of this grant. The self-consistent, single-particle formulation calculates electron phase-space trajectories in order to evaluate the driving source in Maxwell's non-linear wave equation. This is the fundamental mechanism and different regimes of operation or different magnet designs only modify how it occurs.

The self-consistent, non-linear wave equation was developed describing free electron lasers operating in higher harmonics. Self-consistent Coulomb forces were added to the single-particle wave equation with no restrictive assumptions about the form of the periodic electron density. High gain effects were clarified within the wave equation formulation, and found to be responsible for the "symmetrizing" of the gain curve. This effect was previously attributed to Coulomb forces. The above research was published in the IEEE Journal of Quantum Electronics QE-17, 1417 (1981) and is attached.

The scaling properties of the dimensionless wave equation in higher harmonics were used to analyze the possibility of extending the tunable range of free electron lasers to shorter wavelengths. Significant operating gain in the third to eleventh harmonic appears possible when beam quality is excellent. The Orsay storage-ring fel is probably the best candidate for an experiment; they actually plan to try it. This work is published in the Physical Review-Rapid Communications A24, 639 (1981) and is also attached.

Pulse propagation studies have been made much more rigorous and economical by means of the dimensionless wave equation and improved numerical techniques. Since February, we have made several hundred computer runs covering the parameter space of high and low gain, high and low mirror loss, with both short and long electron pulses. A variety of resonator lengths to achieve "desynchronism" are explored in each case. A paper entitled "Optical Pulse Distortion in Free Electron Lasers" by W.B. Colson and J. Eckstein covers part of this research and is now being submitted to Applied Physics.

The distortion of longer optical pulses has been explored with some important results concerning side-band instabilities. Figure 1 shows the evolution of the optical pulse amplitude for 2000 passes in a free electron laser similar to Stanfords. The electron pulse is four times longer than Stanfords and shows break-up into smaller pulses. Side-bands form on either side of the carrier wave frequency as shown in the envelope line-shape in Figure 1. We have verified that this can occur in even longer pulses by modifying the same program to use periodic boundary conditions at the modulation, or side-band wavelength. See Figure 2. These instabilities cannot be easily seen in the Stanford experiment because the pulses are so short; the fourier transform limited linewidth obscures the side-band. But we are finding that they occur over a broad range of conditions and in several varied magnet designs such as the tapered wiggler. While the instability growth has to do with non-linearities, or strong optical fields, it is not necessary to have a large number of synchrotron oscillations (in fact, less than one is possible) as in the Kroll-Rosenbluth analysis. To further show the universality of the instability a paper has been drafted together with R. Freedman in which we develop the Lagrangian formulation for the undulator, the tapered undulated, the optical klystron, and gain expansion. The gain surface (gain as a function of optical wave frequency and amplitude) shows universal features which give broad-band gain in strong fields for any magnet design.

Of particular interest is a direct comparison to the recent Stanford pulse propagation experiments. We find excellent agreement, superior to our previous comparison, and apparently superior to other theoretical approaches. The long "start-up" time measured in the Stanford experiment is not properly part of the coherent pulse problem. Instead, this appears to be explained by insufficient coherence for classical gain due to low photon

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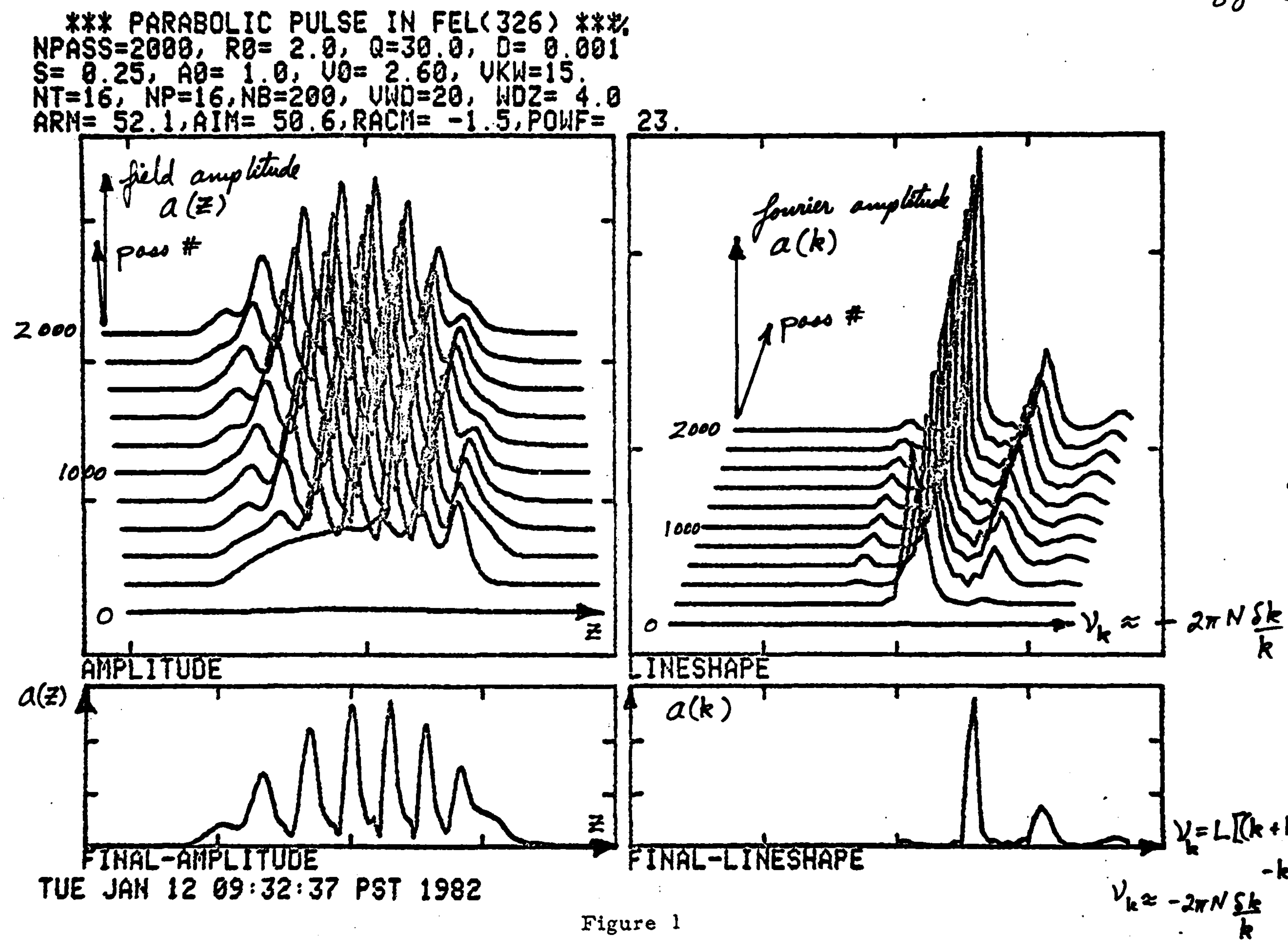

Figure 1

FEL OSCILLATOR EVOLUTION --- PERIODIC BOUNDARY CONDITIONS
4500 PASSES ELECTRON CURRENT R=1.0 CAVITY Q=35.0 V0=2.6
DIMENSIONLESS SLIPPAGE S=0.45 PULSE LENGTH=20 PERIODICITY LENGTHS

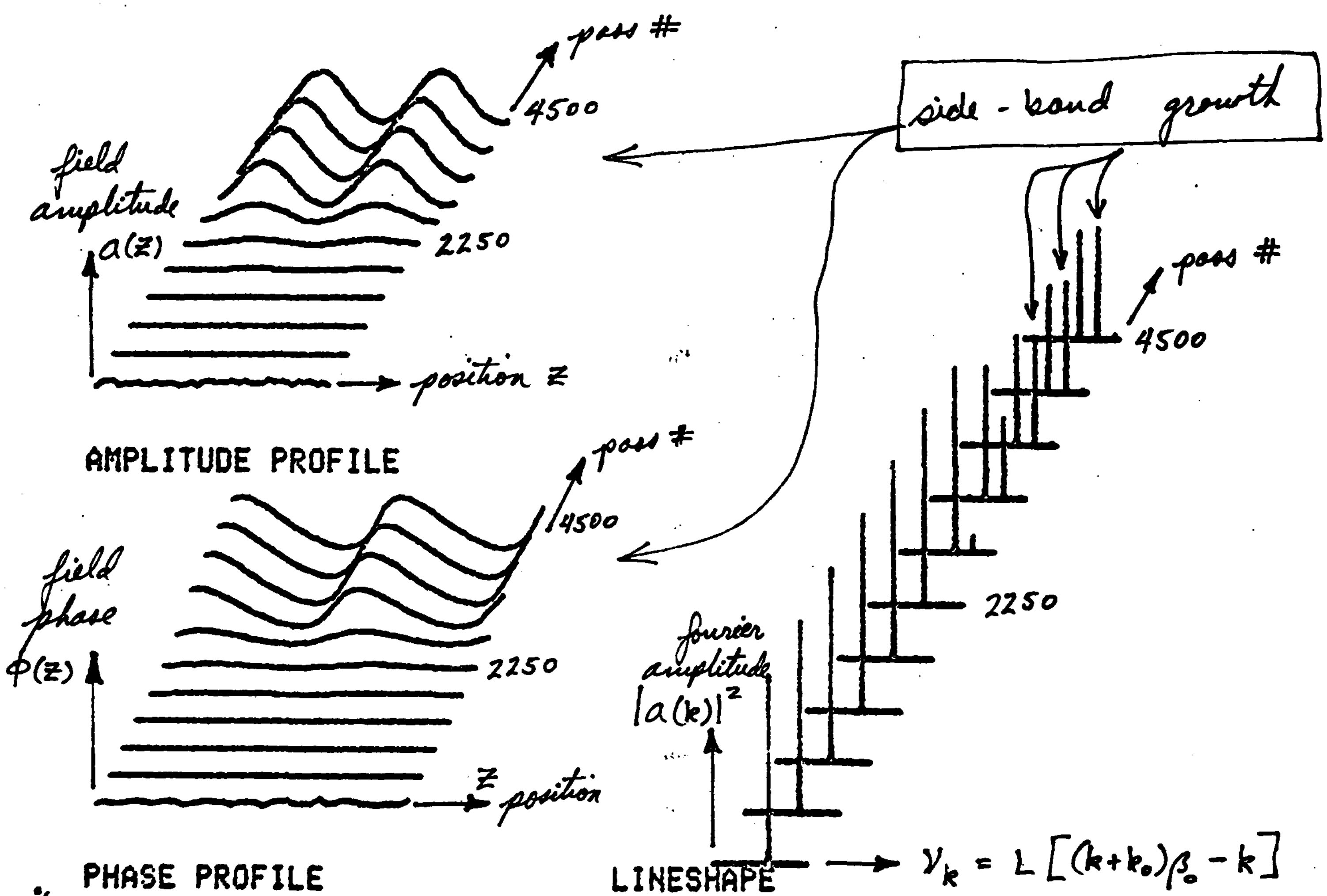

Figure 2

number. The tapered wiggler magnet design has also been explored in the pulse propagation studies, and the Raman, or side-band, instability is observed with or without the tapered wiggler design. The details have been presented at the Sun Valley FEL Workshop and are to be published in those proceedings: Physics of Quantum Electronics, Vol. 8, Chapter 19, page 457 (Addison-Wesley Publishing Co. 1982).

Throughout these studies, graphical representations of optical pulse propagation and electron phase-space evolution has been very helpful in understanding free electron laser physics. Figure 3 gives an example showing the simultaneous evolution of the optical pulse shape a(z), phase profile $\phi(z)$, power spectrum $P(\nu_k)$, and electron distribution function $f(\nu_e)$

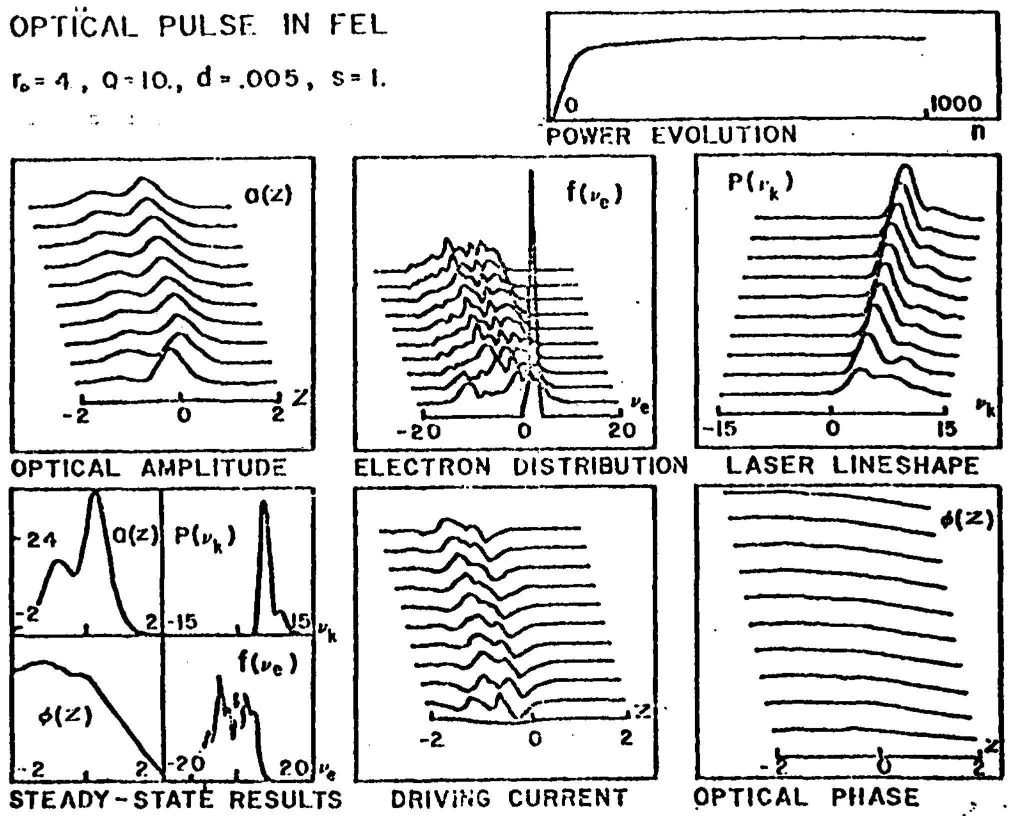

Figure 3

over a thousand passes. Figure 4 shows the same evolution in a tapered wiggler. The graphs not only help in the research, but make communication of our results much easier. To continue along these lines, a camera is included in the renewal budget in order to record computer generated movies of these evolutions.

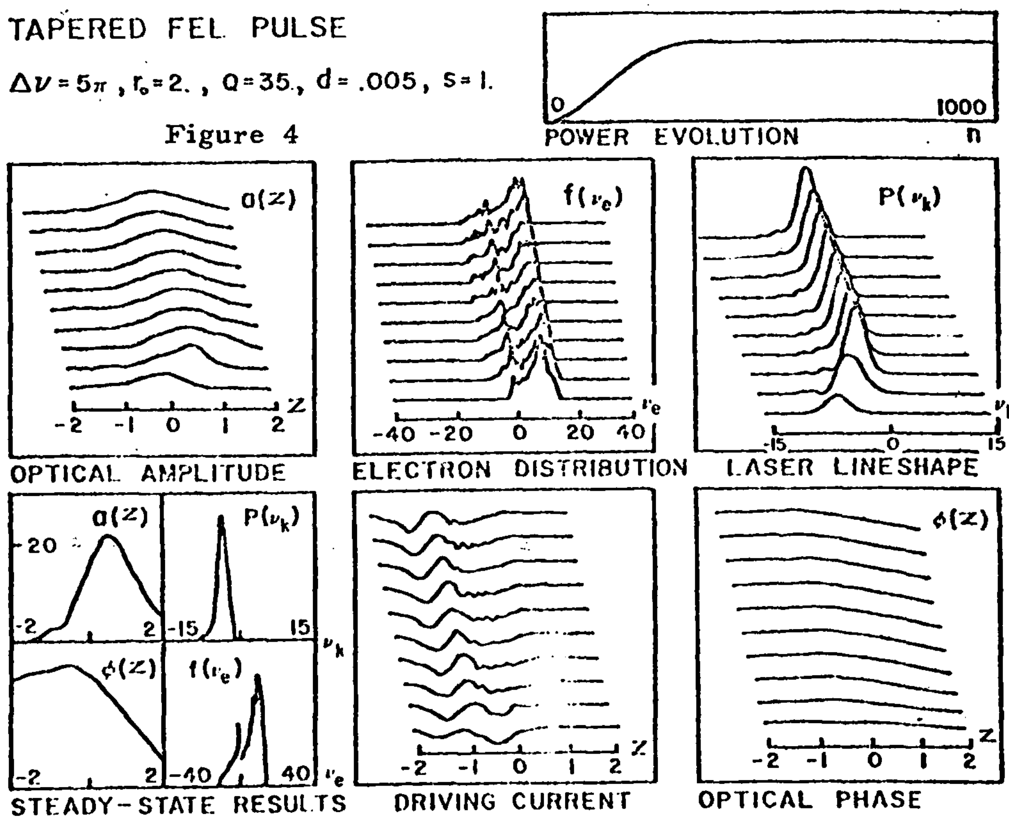

Figure 4

During independent collaboration with two groups (Naval Research Lab and KMS Fusion, Inc.), the effects of longitudinal Coulomb expansion in short electron pulses was explored in both tapered and untapered wigglers. The effect was found to be a generally insignificant problem for normal current densities and pulse lengths. Two short papers are co-authored with these collaborators in the Sun Valley proceedings: Physics of Quantum Electronics, Vol. 8, Chapter 20, page 489, and Chapter 21, page 503 (Addison-Wesley Publishing Co. 1982).

To enhance our understanding of tapered wigglers and their start-up problems, we have calculated the angular and frequency distributions for spontaneous emission. Polarization is also discussed. A draft of a paper exists co-authored with M. Bosco and will be submitted to Physical Review.

We have also developed a numerical program to describe the storage ring operation including a self-consistent klystron, tapered, and untapered wiggler design. In this program we include synchrotron quantum excitations and classical damping, and it will be extended to include pulse shape evolution.

An important extension to all our free electron laser theories is the inclusion of transverse optical wave propagation. Together with a member of the Institute of Theoretical Physics here at UCSB, John Richardson, we now have several operating programs which extend our previous one-dimensional wave/pendulum equations to multiple dimensions (r, z) and (x, y, z). Propagation between mirrors is included. This aspect of our research is just beginning, and we are establishing our numerical accuracy and efficiency. Several new topics will blossom from the programs.

In order to specifically understand electron dynamics in Gaussian spherical wavefronts, we have numerically studied phase-space evolution and gain as a function of the Gaussian mode Rayleigh length z_o. Several free electron designs are considered: the undulator, tapered undulator, and the optical klystron. We find that a proper design of the Gaussian mode can significantly increase gain over the usual plane-wave approximation, and that the gain spectrum is no longer proportional to the slope of the spontaneous emission spectrum. This research was carried out with P. Elleaume of Orsay, France and is being submitted to Applied Physics.

One patent application was submitted to the University of California Board of Patents: UC Case 97-81, "Novel Methods of Tuning Free Electron Lasers to Multiple Wave Lengths." This deals with tuning free electron lasers by moving the mirror axis with respect to the magnet or electron beam axes. Very small angular adjustments can change the wavelength by x2, and could provide multiple users with separate wavelengths.

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